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Electric Measurement of the Critical Current, AC Loss, and Current Distribution of a Prototype HTS Cable

Jiahui Zhu, Zhenyu Zhang, Huiming Zhang, Min Zhang, Ming Qiu, and Weijia Yuan

Abstract—HTS cable is an emerging technology for electricity power transmission. It is very important to set up an accurate and easy-to-build measurement system to characterize HTS cables. In this paper, a novel measurement system has been developed to measure the ac losses for a prototype HTS cable using cancellation coil technique. This system is based on the National Instrument Data Acquisition card. It can also be used to measure the critical current and current distribution in the prototype cable. The prototype cable has been innovatively designed using an improved particle swarm optimization algorithm which is more computationally efficient than conventional methods. The measurement system will be improved further by introducing an elaborate pre-amplifier prior to data collection process and the result will be compared with theoretical calculations for validation.

Index Terms—AC loss, critical current, current distribution, National Instruments Data Acquisition (NI DAQ), prototype HTS cable.

I. INTRODUCTION

SUPERCONDUCTING cables are an emerging and attractive technology for electrical power transmission and distribution due to significant developments of high-temperature superconductors in the past decade. What makes superconducting cables highly desirable for electricity transportation are their high current density and low energy loss. This leads to four major benefits over conventional counterparts [1], [2]: i) they are significantly safer and cheaper to operate as the same amount of power can be transported at a much lower voltage, ii) their power transmission capacity in the same volume is up to ten times larger (including the cooling system) than conventional underground cables and overhead cables, thus the right-of-way requirement is substantially reduced, iii) their resistive losses are only one third of conventional cables even after including the cooling power, iv) magnetic field leakage, with its associated environmental impact, can be eliminated by

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inclusion of a superconducting shielding layer. As a result of these characteristics, superconductors offer an attractive alternative to conventional energy transmission in supporting energy transportation from distant renewable generation as well as in relieving electricity transportation congestion in metropolitan cities.

A novel characterization system has been developed to characterize a prototype HTS cable in the University of Bath, U.K. Using Labview and NI data acquisition modules, this system has an integrated design. It can characterize the current currents, ac losses, and current distributions of HTS samples using one control interface. In particular, the ac losses measurement is using an electric method—cancellation coil technique, which is much faster than a calorimetric method. It can also be used to characterize different samples such as tapes and coils. A 132 kV/1.2 kA cable structure has been optimally designed to minimize the current difference in each conductor layer using an improved particle swarm optimization (PSO) algorithm. A short prototype has been constructed based on this design. Its critical current, ac loss, and current distribution have been characterized using the developed measurement system to validate the cable's design work.

II. EXPERIMENT SYSTEM DESIGN

A. Critical Current Measurement System

In this paper, the critical current values of HTS samples are measured using 1 uV/cm criterion at self-field condition, 77 K operating temperature, with no bending. A control program based on Labview and NI data acquisition module was developed. A dc power supply is controlled by a Labview interface panel. The ramp rate of the applied current can be set at various values (1 A/s, 2 A/s, and 4 A/s). The protection of HTS samples is essential. A thermal resistor (PT100) was used to monitor the operation temperature. The upper limit voltage across the HTS sample, beyond which the ramping current will be stopped, was set at 10 times of the critical voltage.

The general critical current measurement system panel is shown in Fig. 1 and the flow chart in Fig. 2 presents the working principle of the measurement system.

The measured voltage contains an inductive component of the HTS sample (a coil or a cable), as in (1). This voltage $L_s(di/dt)$ is induced when the current is increasing. It should be removed from the measured voltage V_m for accurate critical current values.

$$V_m = L_s \frac{di}{dt} + V_s. \quad (1)$$

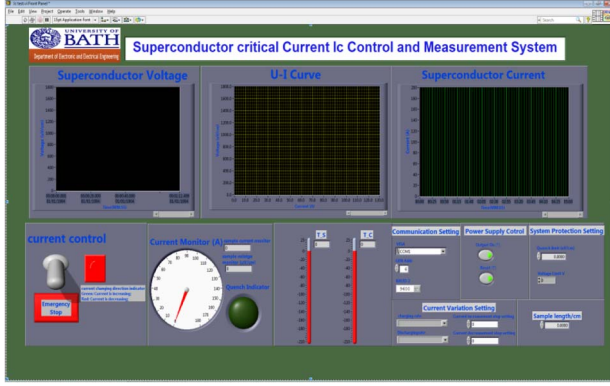


Fig. 1. Control panel of the critical current measurement system.

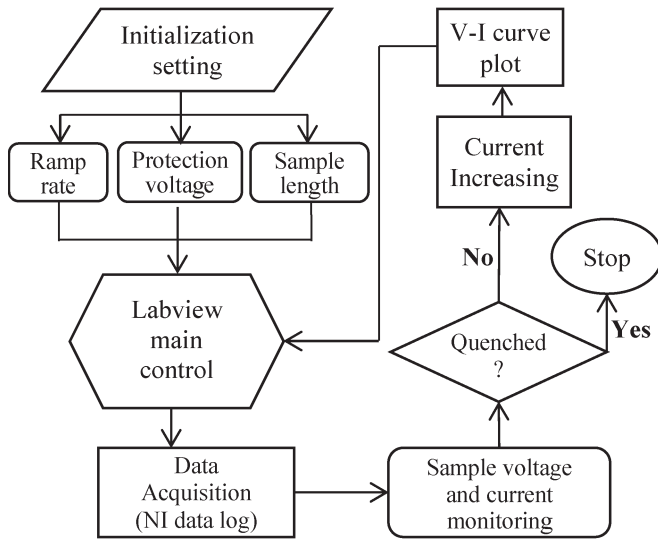


Fig. 2. Flow chart of general critical current measurement procedure for HTS samples.

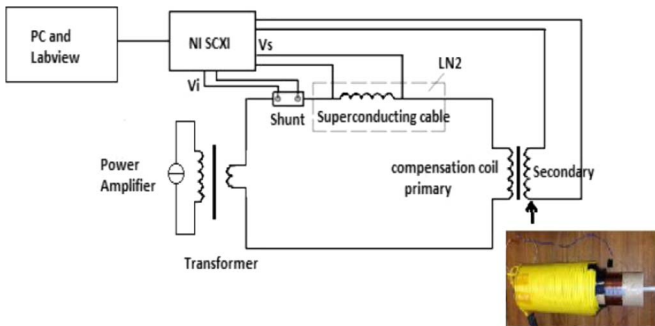


Fig. 3. Circuit diagram of ac loss measurement.

B. AC Loss Measurement of HTS Cable

The ac losses of HTS cables are essential information for the design of cryogenic systems. Fig. 3 shows the overall ac loss testing circuit diagram. The ac loss measurement system panel is shown in Fig. 4. Since the cable produces a large inductive voltage, a cancellation coil has been developed to cancel the inductive voltage so as to leave only resistive voltage to measure [3], [4].

The measured voltage V_s (shown in Fig. 3) of the HTS cable includes two components: a resistive voltage RI due to

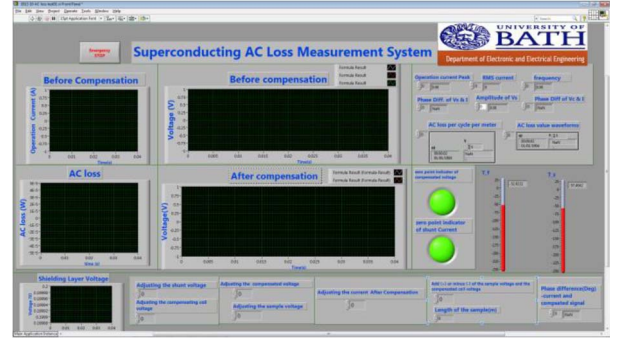


Fig. 4. Control panel of the ac loss measurement system.

the hysteresis loss and an inductive voltage due to the large self-inductance and mutual inductance between the conductor layers.

$$V_s = RI + j\omega LI. \quad (2)$$

Only the resistive component in (2) represents the ac loss voltage [5]. The mutual inductance of the compensation coil M can be adjusted by shifting the secondary coil, while the inductive component V_s is minimized by subtracting the voltage of the secondary coil voltage $V_c = j\omega MI$ from V_s . When M is equal to L , the resulting voltage V_r is purely resistive, as shown in (3):

$$V_r = V_s - V_c = RI + j\omega(L - M)I = RI. \quad (3)$$

The resulting voltage V_r is in phase with the current I flowing through the HTS cable, and the multiplication of in-phase resulting voltage and transport current gives the ac loss, as shown in (4):

$$Q = \frac{V_r \cdot I}{l \cdot f} \text{ (J/m/cycle)}. \quad (4)$$

Where: l is the length of the HTS conducting layer of the cable and f is the frequency of transport current.

An alternative method is using a lock-in amplifier to measure the phase difference θ between V_s and I , then the in-phase voltage V_R can be obtained from $V_R = V_s \cdot \cos \theta$. And the ac loss can be calculated using (5):

$$Q = \frac{V_R \cdot I}{l \cdot f} \text{ (J/m/cycle)}. \quad (5)$$

C. Current Distribution Measurement of the Prototype Cable

The current sharing issue is an important design aspect for an ac HTS cable for power transmission. Due to the self- and mutual inductance, there might be different transport currents flowing in different layers. To minimize the ac loss, the transport current needs to be equally shared between different layers. An improved particle swarm optimization method has been used for optimization. The optimization procedure can be found in [6].

A circuit model can represent a multilayer structure of HTS cable, as shown in Fig. 5 [7]. Due to the relatively large inductance, the resistance of each layer can be ignored in current sharing calculation. The inductance values of each layer are different due to various radii and pitch angles. The current

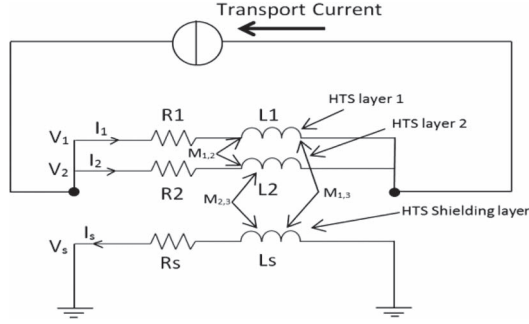


Fig. 5. Circuit model of a multilayer HTS cable.

 TABLE I
PARAMETERS OF THE PROTOTYPE HTS CABLE

Characteristics	Item	Value
Copper former	Radius	9 mm
1 st conducting layer (BSCCO)	Radius	10.4 mm
	Pitch angle	20°
	Tape number	8
2 nd conducting layer (BSCCO)	Radius	10.8 mm
	Pitch angle	11°
	Tape number	9
PPLP insulation layer	Radius	24.5 mm
1 st shielding layer (BSCCO)	Radius	24.9 mm

flowing through each layer is affected by the self- and mutual inductances and therefore can be changed by adjusting the pitch angle and radius. The design variables are presented in (6). The objective function for minimization is presented by (7), which represents the current difference in different conductor layers.

$$X = [\alpha_1, \alpha_2, \dots, \alpha_n, r_1, r_2, \dots, r_n] \quad (6)$$

$$G(X) = \min F(X) = \min \left(\sum_{i=1}^{n-1} \sum_{j=i+1}^n |I_i(X) - I_j(X)| \right) \quad (7)$$

Where: X is a vector containing the pitch angles α and radii r of each HTS conductor layer, n is the number of total layers, $i, j = 1, 2, \dots, n$, $G(X)$ is the objective function.

III. EXPERIMENT AND ANALYSIS

A. Prototype HTS Cable and the Test System

The structure parameters of a 132 kV/1.2 kA prototype HTS cable after current sharing optimization are shown in Table I.

Two layers of BSCCO tapes are helically wound on a copper former to form a prototype HTS cable, as shown in Fig. 6. An insulation layer was wrapped around the outer conducting layer and a BSCCO HTS shielding layer was wound on top of the insulation layer. A bundle of copper strings is used as the current lead of this HTS cable.

Fig. 7 presents the picture of the experimental system. The system includes a dc/ac power supplier, a power amplifier, a NI data acquisition, a Labview interface panel and LN2 tank. The shunt and the compensation coil are used for the testing of the critical current and ac loss of HTS cable.

B. Measurement Results and Analysis

First, the measurement system has been used to measure the critical currents of HTS thin tapes, BSCCO coils, and HTS

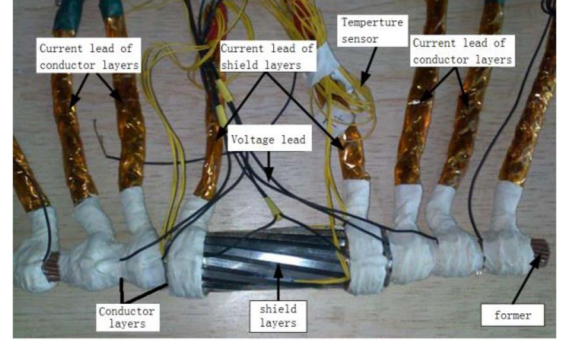


Fig. 6. 0.2 m, 132 kV/1.2 kA prototype HTS cable.

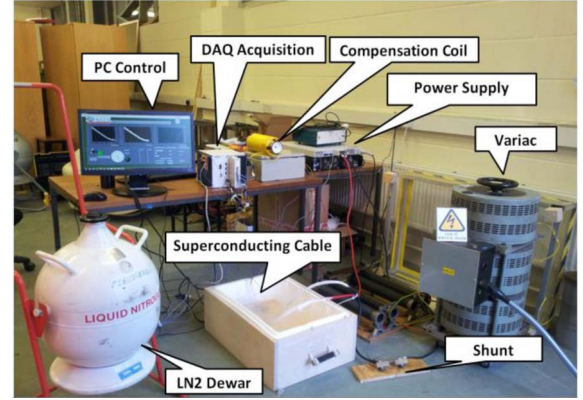


Fig. 7. Setup of the HTS cable measurement system.

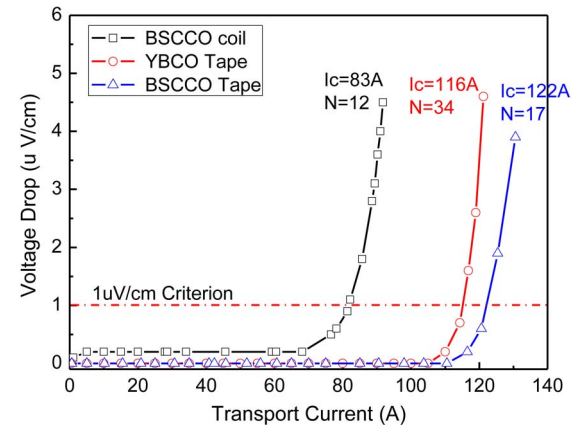


Fig. 8. Summary of the critical current test results of YBCO tape, BSCCO tape, and BSCCO coil.

cables. The critical currents of the HTS tapes and coils are measured to validate the function of the measurement system. The results are plotted and summarized in Fig. 8. The “ n ” values were calculated based on the equation: $E/E_c = (I/I_c)^n$, where E_c is $1 \mu\text{V/cm}$ and I_c is the relevant critical current value. The critical current of the BSCCO coil is 83 A which is 68% of that of the BSCCO tape due to the interaction between I_c and self-magnetic field.

The critical current measurement of the prototype cable is presented in Fig. 9. We can find that from $I = 1500$ A there is a clear sharp rise in the cable voltage. Therefore the critical current can be determined as 1500 A. There is about 20%

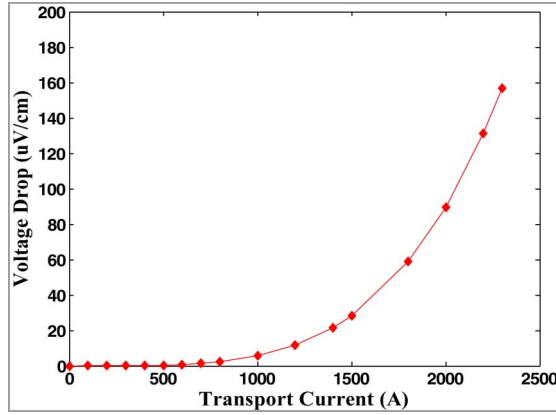


Fig. 9. Critical current testing result of prototype HTS cable.

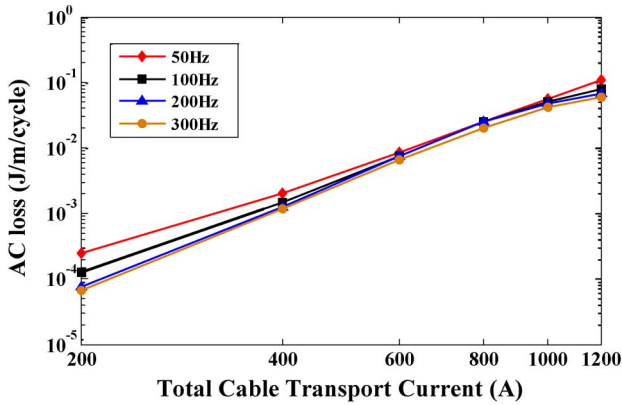


Fig. 10. AC loss testing results of the prototype HTS cable at various frequencies.

safety margin if the cable operates at 1200 A as shown in our design.

According to the design (Table I), 17 BSCCO tapes are required to construct this two-layer cable. So the critical current in theory is $17 \times 122\text{ A} = 2074\text{ A}$. And the actual critical current 1500 A is 72.3% of the theoretical current. This degradation is due to the interaction between I_c and self-magnetic field when the BSCCO tapes are wound into a cable.

Second, the results of ac loss under various testing frequencies based on the lock-in amplifier method are summarized in Fig. 10 using a power supplier with 0–200 Hz, 0–3000 A. It can be seen that the ac loss per cycle is approximately proportional to the I^3 [8] and is independent of the frequencies.

Finally, the ac transport currents flowing through each superconducting layer in a HTS cable are measured by applying Rogowski coils wrapped around the current lead of each HTS layer. The data are recorded by a high accuracy NI acquisition system which is similar with the critical current measurement system. An ac current flows through this HTS cable, such as 800 A which is less than the rated current 1200 A, for the safety operation. The measurement result is presented in Fig. 11. The testing current of each layer is not exactly evenly distributed due to the inaccurately controlled pitch angle during the cable constructing process.

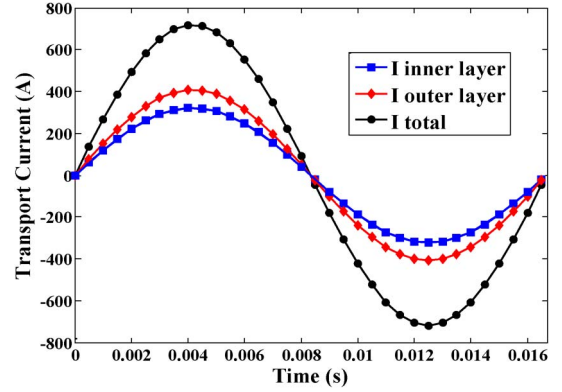


Fig. 11. Current distribution testing results of HTS cable at 60 Hz.

IV. CONCLUSION

A novel HTS characterization system with a visual interface panel has been developed based on National Instruments data acquisition cards and Labview program. This system has an integrated design and can measure critical currents, ac losses and current distribution of HTS cables. A 0.2-m-long, 132 kV/1.2 kA prototype two-layer HTS cable has been optimally designed and constructed. The cable design has used an improved PSO algorithm to minimize current difference in conductor layers. The characteristics of the cable including ac losses and current sharing have been experimentally studied. The measurement result validates the design which can share the same ac transport current in each conductor layer. The measurement system will be improved further by introducing an elaborate pre-amplifier prior to data collection process and the result will be compared with theoretical calculations for validation.

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